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Static Power Conversion for Spacecraft

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Static power conversion for spacecraft

As spacecraft increase in complexity, power conditioning becomes an increasingly important, sophisticated aspect of systems design

BY TERRY W. KOERNER Repr. from Astronautics and Aerospace Eng., May 1963 p 89-92

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Reprint

The spacecraft's power-conversion equipment has the primary purpose of matching characteristics of primary power or energy source and the load. This equipment can be divided into two general categories: static and dynamic. During the last several years, static systems have been generally favored for spacecraft use because of relatively light weight for the power levels involved, absence of gyroscopic forces, and potentially long life. This paper discusses characteristics of static systems for medium power levels and problems of matching power sources to the load.

There have been two general classes of spacecraft—satellites and lunar or planetary probes. Power systems for satellite use are generally characterized by relatively high cyclic rates. Periods on the order of 90 min are typical, requiring that solar-powered satellites employ high charging rates to avoid excessive weight penalties in batteries. Solar-powered satellites are very strongly dependent on energy storage systems because of the periodic loss of solar power. Lunar and planetary spacecraft, on the other hand, are characterized by long periods of cruise involving only solar power. Energy-storage devices are used only during sun-acquisition and maneuvers.

The characteristics of the energy or power sources are important considerations in the design of the conversion subsystem. The most widely used sources have been solar panels and batteries. Satellites have generally used nickel-cadmium batteries, because they allow a large number of charge cycles. The silver-zinc battery tends to be favored for lunar and planetary missions because of its greater watt-hour capacity per pound of weight. The limited number of charge cycles permitted by the silver-zinc battery is not a serious limitation for lunar or planetary spacecraft. In general, batteries have a very flat regulation curve, as indicated in the first graph on page 90.

Solar panels have a relatively high and varying source impedance. A typical solar-panel characteristic curve is given in the graph just cited. Near the open-circuit end, the characteristic curve looks like that of a battery having rather poor regulation. On the short-circuit end of the characteristic curve the solar panels closely approximate a current source.

The thermoelectric couple appears promising as a power source, particularly with radioisotope heat sources. It has a nearly constant output impedance, its voltage-current characteristic curve being indicated in the first graph.

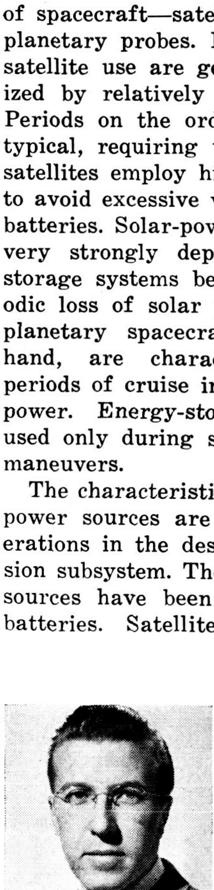
The thermionic diode is also a very promising power source, primarily because of its potentially high efficiency. The voltage-current characteristics of the thermionic diode very strongly depend on the mode in which it is operated, particularly with regard to the cathode temperature and the cesium-reservoir pressure. Again, the first graph shows a characteristic curve.

The regulation characteristics of the power or energy source have a strong effect on two design considerations for the regulation and conversion equipment.

The first and most obvious of these is the effect of a load variation on the range of input voltage. Besides voltage variations of the source caused by changes in environment, there will be an input-voltage variation owing to load changes. The latter variation has greater consequence on a high-impedence source. Both variations must be taken into account when designing the regulating equipment.

The second occurs in power systems employing duty-cycle control to maximize efficiency of the conversion system. Input-current waveform for this type of system without an input filter is discontinuous, and for low-impedance sources approximates a square wave. A drawing on page 90 shows a typical current waveform when operating from a battery. The chief effect of this varying input current waveform is to reduce the power that may be drawn from the source, especially a high-impedance source.

This effect may be made somewhat more obvious by redrawing the voltage-current curves shown by the first graph on page 90 in the form of the power-vs.-voltage curves shown in the center graph. The greatest power that can be drawn from a source occurs when the peak-power demand of the regulator equals the maximum power capability of the source. Since the regulator is not drawing power for



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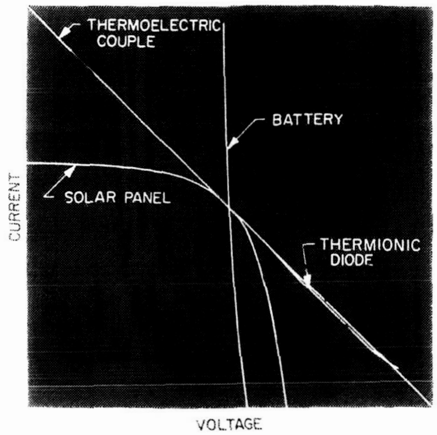
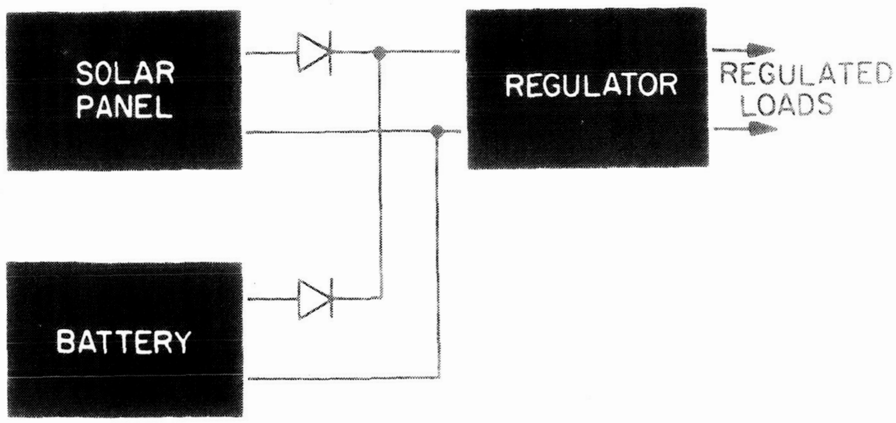


Voltage current characteristics.

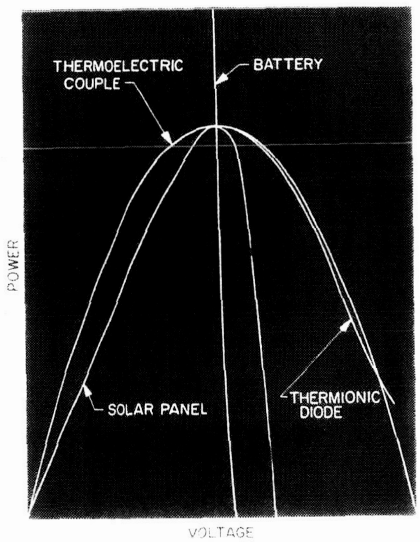


Diode logic for power source selection.

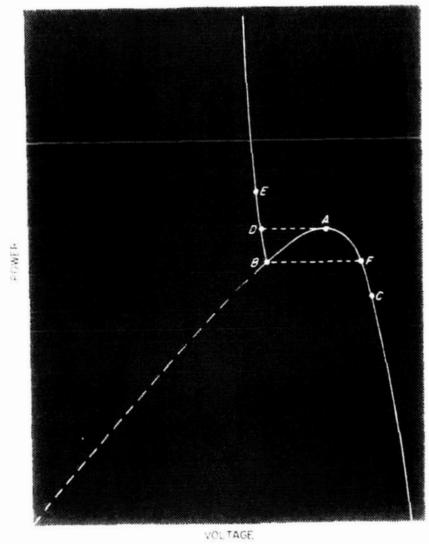
a portion of a cycle, the average power drawn from the source may be appreciably less than its maximum power capability. This effect may be reduced to the extent desired by providing input filtering for the regulator, either in the form of the simple capacitor across the source or a choke-capacitor low-pass filter. As the input filter on a regulator is increased in energy storage, the ratio of average power demand to peak-power demand approaches unity, and the operating point for the regulator may approach the maximum power point of the source.

Two or more of the sources indicated may be used in a spacecraft to satisfy mission requirements. One means of selecting the source to be used is to provide a change-over switch that can be activated by ground command, by on-board timer, or possibly by on-board sensors. An alternate, and somewhat more foolproof scheme is to use blocking diodes from each of the sources, as indicated in the diagram top right. In this configuration whichever source has the highest voltage carries the load, although there may be times when both sources are operating. A composite source characteristic may then be drawn for the combination.

The graph below the diagram shows an example of such a composite curve for a solar panel and battery combination. Note that for a nondissipative regulator, represented by a horizontal straight line in the power-voltage plane, a region of power exists for which there are apparently three operating points. Actually, the region of the composite curve having a positive slope is not a region of stable operation for this type of regulator.



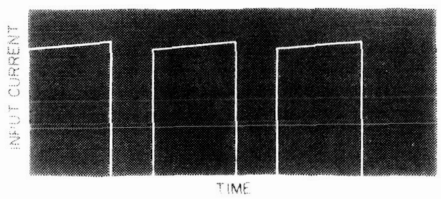
Power vs. voltage for various sources.



Solar panel and battery combination.

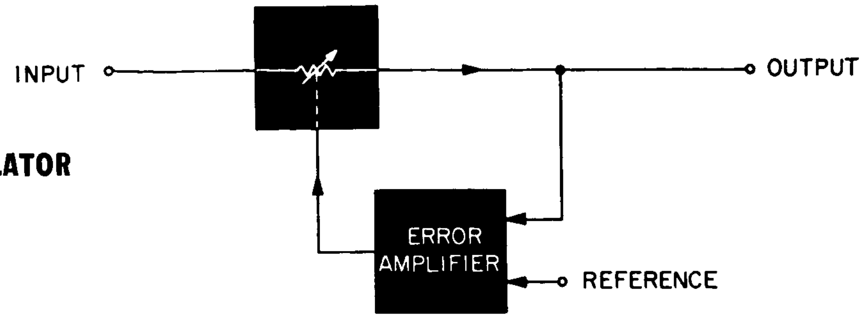
In this graph the vertical distance between the points A and B represents a power hysteresis. If the initial operating point on the composite curve is point C, for example, and the load on the regulator gradually increased, the operating point will traverse the composite curve from C until it reaches A. At this point a region of instability is entered. The operating point very quickly traverses the composite curve from A to B and then to D. At point D stable operation again occurs. If the load is further increased the operating point moves up the composite curve from D to E. If the load is now slowly reduced, the operating point moves down the composite curve from point E to point B. At point B the region of instability is again entered and the operating point very quickly traverses the composite curve from B through A to F, where stable operation again occurs.

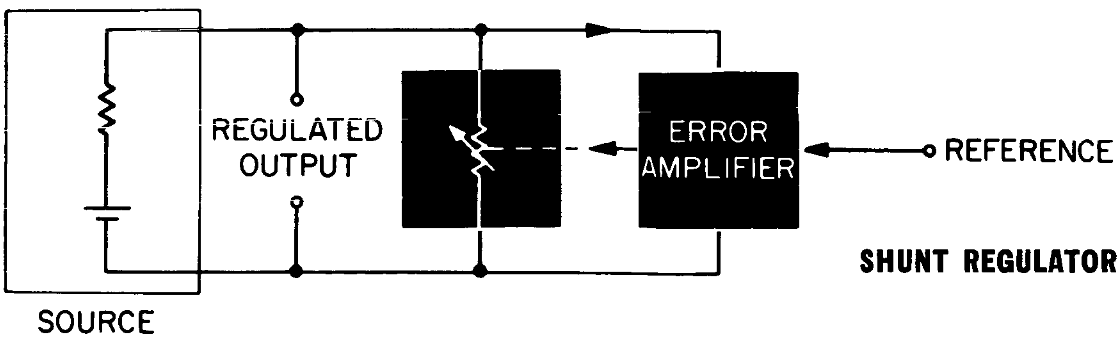
By tracing the operating point on the composite curve through such a load variation, it becomes obvious that, although the panels can support a maximum load indicated by point A, if the load exceeds the level of point A even momentarily the operating point will shift to the left-hand portion of the curve. The load must then be reduced to the level indicated by point B to return to operation on the right-hand side of the curve. Since the voltage at point B is the open-circuit battery voltage, operation on the composite curve in the region of points D and E represents some drain upon the battery. This is an undesirable condition for cruise. To eliminate power-sharing with the battery, it is evident that the load must not exceed the power capability of the solar panels at



Input-current waveshape for unfiltered regulator with duty cycle control.

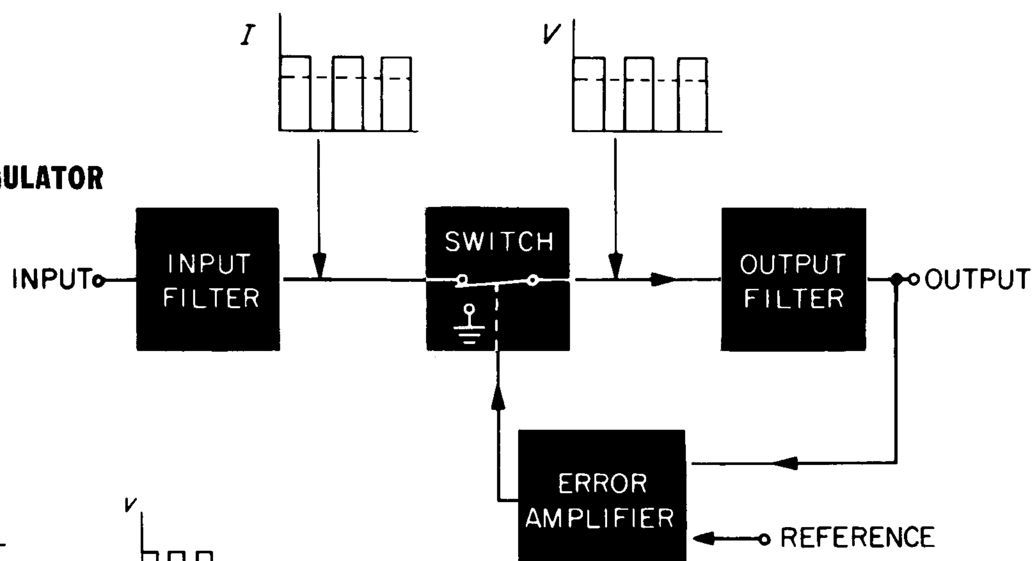
SERIES DISSIPATIVE REGULATOR

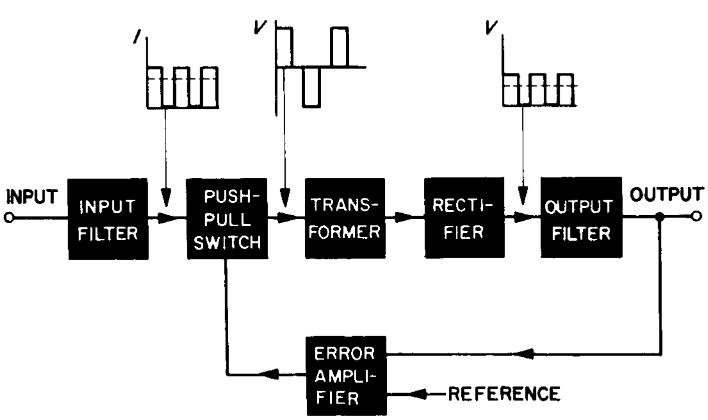




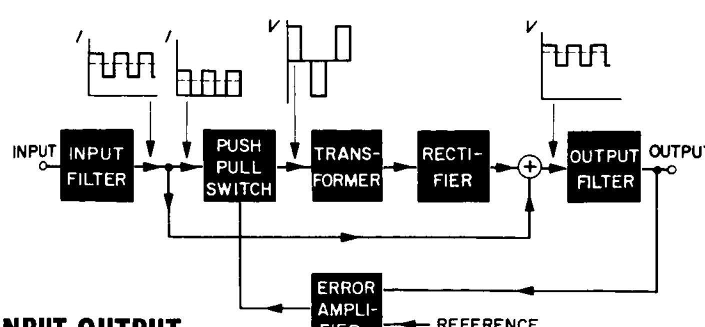
SHUNT REGULATOR

SWITCHING REGULATOR





REGULATING CONVERTER



BOOSTER INPUT-OUTPUT

point B, rather than the maximum power capability of the panels, as indicated by point A, unless additional means are used to return the operating point to the right-hand side of the curve.

It is desirable to minimize the hysteresis, since in effect it is a derating of the solar-panel power capability. The most obvious solution is to make points A and B coincident. The difficulty with this solution is that there are appreciable uncertainties in the positions of both points A and B. These occur as a result of design uncertainties, environmental changes, and variations in time during the mission. If points A and B are made coincident in the nominal case, a condition might occur in flight in which point B would actually be appreciably to the right of point A. If this were to occur, the battery might carry a small portion of a spacecraft load continuously, resulting in an eventual depletion of the battery and possibly failure of the mission.

There are several types of regulators that can be used to achieve the desired load regulation, probably the simplest being the series dissipative regulator indicated in block-diagram form on page 91. In this type of regulator the output voltage is compared with the reference voltage, and the error operates a variable series element. The input voltage is always greater than the output voltage. The product of the difference voltage and the output current is dissipated. There is also a small loss associated with the operation of the error amplifier and reference. This type of regulator can be very inefficient if the input voltage excursion is large. Also, the series element is usually a large transistor; since it must be capable of dissipating relatively large amounts of power, careful design of its heat sink is a requirement.

The shunt regulator, shown diagrammatically on page 91, represents an alternative suitable for operation from high-impedance sources. In this device the error amplifier controls a variable load across the source. This device maintains an essentially constant total load on the source, thus achieving regulation of the output. The variable load must be capable of dissipating the difference between the maximum power capability of the source and the minimum load. The device also tends to be rather inefficient, especially if the ouput load range is large.

There are several forms of the so-called nondissipative regulator. One of these, the switching regulator, shown in block-diagram form on page 91, is similar to the series dissipative regulator, except that a duty-cycle-controlled switch is used, rather than a series dissipative element. Input and output filters provide necessary averaging of the pulse waveforms indicated in the block diagram. As in the series dissipative regulator, the output is always less than the input voltage. The reference input indicated in the diagram usually takes the form of a zener diode. In many instances, a temperature-compensated zener diode is used, followed by a transistorized differential amplifier.

There are several methods of obtaining a variable duty cycle from the error signal. One method makes use of a square-wave oscillator that drives a ramp generator. The amplified error signal is compared to the level of the ramp in a one-shot circuit that switches when the ramp and the amplified error signal are of equal magnitude. Variation in the error signal thereby controls the timing of the switch. The ramp generator is usually reset to zero each half cycle, simultaneously with the reversal of the oscillator output.

An alternate approach uses a magnetic amplifier to control the pulse width of the switch. The amplified error signal is applied to the control winding of the mag-amp, regulating the amount of resetting of the core. A constant-amplitude square-wave signal is applied to the gate winding of the magnetic amplifier from a separate oscillator. The time required to saturate the core depends on the amount of core reset; and the width of the output pulse thus depends on the control current in the control winding.

A third method of generating a variable pulse-width for the switch drive incorporates two square-wave oscillators, a master and a slave. The two oscillators operate synchronously, but with a variable time delay between the master and slave controlled by the amplified error signal. If the oscillator outputs are held at equal amplitudes, they may be summed to give a bidirectional square wave of varying width. This signal may be rectified to produce the required drive signal to the switch.

The block diagram of a regulating converter appears at the top of page 91. This device usually consists of two duty-cycle-controlled switches operating in push-pull, with output transformed to the proper voltage level and rectified to provide the required DC output. Current and voltage waveforms at various points in the circuit are indicated in the figure.

The error amplifier senses deviations in average output voltage and controls the duty cycle of the switches accordingly. The mechanizations of the error amplifier and switch drive are very similar to those described for the switching regulator, except that a bidirectional drive is required because of the push-pull operation of the switches.

A booster is very similar to a regulating converter, except that the input voltage is added to the output of the rectifier before filtering. A block diagram of a booster appears on page 91. As the name implies, the output voltage of a booster is always higher than the input voltage. The power handled by the switches in a booster is determined by the load current and the difference in voltage between the input and output, whereas in the regulating converter all the power must be handled by the switches. Also, the duty cycle of a booster usually ranges from nearly zero to almost 100%, in order to cover the input voltage range. In a regulating converter the duty cycle would not approach zero during normal operation. A unit having a two-to-one range of input voltage would have a minimum duty cycle on the order of 50%, for example.

Efficiency of the nondissipative regulators ranges from 75 to over 90%, depending on power level, input voltage range, output voltage, and type of semiconductor switches used. All other factors being equal, the booster tends to have a somewhat higher efficiency than a regulating converter since only a portion of the power is being handled by the switches. The efficiency of duty-cycle-controlled regulators usually varies less than 5% over the entire voltage range. The way in which it varies with voltage depends strongly on the relative magnitudes of conduction losses and switching losses.

An inherent limitation of all of the nondissipative regulators is the limited rate of response to changes in load current. This occurs primarily as a result of the employment of choke-capacitor filtering in the output of the regulators to obtain essentially loss-less filtering. The time constants involved with this filter set an upper limit to the speed of response of the regulator. Dissipative regulators, on the other hand, suffer no such limitations, their rate of response being limited primarily by loop stability considerations involved with the time constants of the semiconductor devices employed.

In spite of limitations in response time, however, nondissipative regulators are being widely used throughout the spacecraft industry. The power savings they afford and the simplification of the design of heat sinks for the regulation equipment make their use almost mandatory in the larger power systems. ●●